Top-quark pair production impact on CTEQ PDFs of the proton

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for the **CTEQ-TEA (Tung Et. Al.)** working group

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SnowMass2021

Energy Frontier Workshop - Restart, Sep 2, 2021

EF03: EW Physics: Heavy flavor and top quark physics

EF06: QCD and strong interactions: Hadronic structure and forward QCD

KENNESAW STATE UNIVERSITY

The CT18 analysis

PHYSICAL REVIEW D **103,** 014013 (2021)

Editors' Suggestion

New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC

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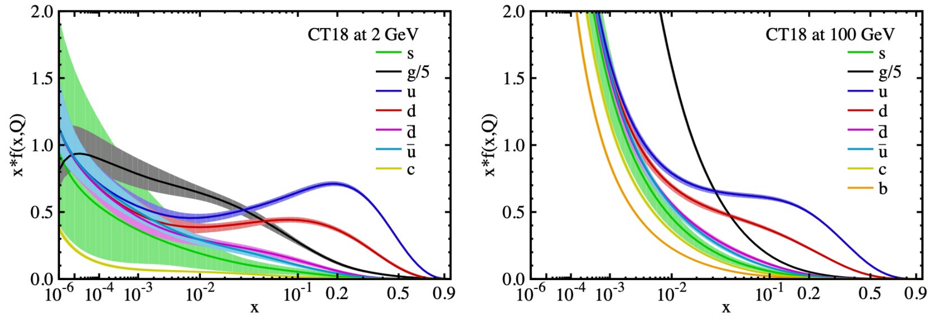


TABLE I. Datasets included in the CT18(Z) NNLO global analyses. Here we directly compare the quality of fit found for CT18 NNLO vs CT18Z NNLO on the basis of χ^2_E, $\chi^2_E/N_{pt,E}$, and S_E, in which $N_{pt,E}$, χ^2_E are the number of points and value of χ^2 for experiment E at the global minimum. S_E is the effective Gaussian parameter [38,42,56] quantifying agreement with each experiment. The ATLAS 7 TeV 35 pb^{-1} W/Z dataset, marked by ‡‡, is replaced by the updated one (4.6 fb^{-1}) in the CT18A and CT18Z fits. The CDHSW data, labeled by †, are not included in the CT18Z fit. The numbers in parentheses are for the CT18Z NNLO fit.

Exp. ID#	Experimental dataset		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
160	HERAI + II 1 fb^{-1}, H1 and ZEUS NC and CC $e^{\pm}p$ reduced cross sec. comb.	[30]	1120	1408 (1378)	1.3 (1.2)	5.7 (5.1)
101	BCDMS F_2^p	[57]	337	374 (384)	1.1 (1.1)	1.4 (1.8)
102	BCDMS F_2^d	[58]	250	280 (287)	1.1 (1.1)	1.3 (1.6)
104	NMC F_2^d/F_2^p	[59]	123	126 (116)	1.0 (0.9)	0.2 (−0.4)
108†	CDHSW F_2^p	[60]	85	85.6 (86.8)	1.0 (1.0)	0.1 (0.2)
109†	CDHSW $x_B F_3^p$	[60]	96	86.5 (85.6)	0.9 (0.9)	−0.7 (−0.7)
110	CCFR F_2^p	[61]	69	78.8 (76.0)	1.1 (1.1)	0.9 (0.6)
111	CCFR $x_B F_3^p$	[62]	86	33.8 (31.4)	0.4 (0.4)	−5.2 (−5.6)
124	NuTeV $\nu\mu\mu$ SIDIS	[63]	38	18.5 (30.3)	0.5 (0.8)	−2.7 (−0.9)
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	[63]	33	38.5 (56.7)	1.2 (1.7)	0.7 (2.5)
126	CCFR $\nu\mu\mu$ SIDIS	[64]	40	29.9 (35.0)	0.7 (0.9)	−1.1 (−0.5)
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	[64]	38	19.8 (18.7)	0.5 (0.5)	−2.5 (−2.7)
145	H1 σ_r^b	[65]	10	6.8 (7.0)	0.7 (0.7)	−0.6 (−0.6)
147	Combined HERA charm production	[66]	47	58.3 (56.4)	1.2 (1.2)	1.1 (1.0)
169	H1 F_L	[33]	9	17.0 (15.4)	1.9 (1.7)	1.7 (1.4)
201	E605 Drell-Yan process	[67]	119	103.4 (102.4)	0.9 (0.9)	−1.0 (−1.1)
203	E866 Drell-Yan process $\sigma_{pd}/(2\sigma_{pp})$	[68]	15	16.1 (17.9)	1.1 (1.2)	0.3 (0.6)
204	E866 Drell-Yan process $Q^3 d^2\sigma_{pp}/(dQ dx_F)$	[69]	184	244 (240)	1.3 (1.3)	2.9 (2.7)
225	CDF run-1 lepton A_{ch}, $p_{T\ell} > 25$ GeV	[70]	11	9.0 (9.3)	0.8 (0.8)	−0.3 (−0.2)
227	CDF run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV	[71]	11	13.5 (13.4)	1.2 (1.2)	0.6 (0.6)
234	DØ run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV	[72]	9	9.1 (9.0)	1.0 (1.0)	0.2 (0.1)
260	DØ run-2 Z rapidity	[73]	28	16.9 (18.7)	0.6 (0.7)	−1.7 (−1.3)
261	CDF run-2 Z rapidity	[74]	29	48.7 (61.1)	1.7 (2.1)	2.2 (3.3)
266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	[75]	11	7.9 (12.2)	0.7 (1.1)	−0.6 (0.4)
267	CMS 7 TeV 840 pb^{-1}, electron A_{ch}, $p_{T\ell} > 35$ GeV	[76]	11	4.6 (5.5)	0.4 (0.5)	−1.6 (−1.3)
268‡‡	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	[77]	41	44.4 (50.6)	1.1 (1.2)	0.4 (1.1)
281	DØ run-2 9.7 fb^{-1} electron A_{ch}, $p_{T\ell} > 25$ GeV	[78]	13	22.8 (20.5)	1.8 (1.6)	1.7 (1.4)
504	CDF run-2 inclusive jet production	[79]	72	122 (117)	1.7 (1.6)	3.5 (3.2)
514	DØ run-2 inclusive jet production	[80]	110	113.8 (115.2)	1.0 (1.0)	0.3 (0.4)

TABLE II. Like Table I, for newly included LHC measurements. The ATLAS 7 TeV W/Z data (4.6 fb^{-1}), labeled by ‡, are included in the CT18A and CT18Z global fits, but not in CT18 and CT18X.

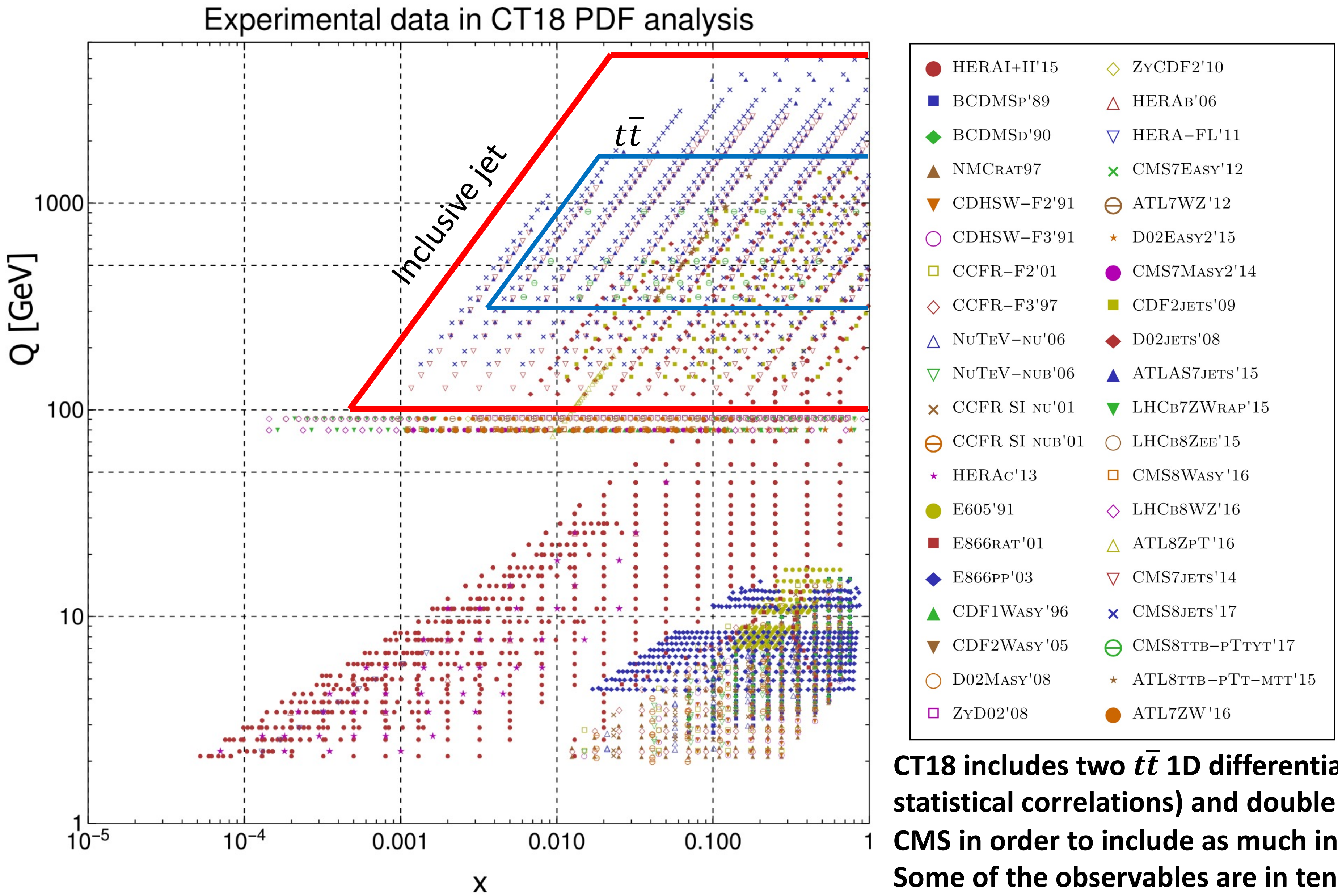
Exp. ID#	Experimental dataset		$N_{pt,E}$	χ^2_E	$\chi^2_E/N_{pt,E}$	S_E
245	LHCb 7 TeV 1.0 fb^{-1} W/Z forward rapidity cross sec.	[81]	33	53.8 (39.9)	1.6 (1.2)	2.2 (0.9)
246	LHCb 8 TeV 2.0 fb^{-1} $Z \to e^- e^+$ forward rapidity cross sec.	[82]	17	17.7 (18.0)	1.0 (1.1)	0.2 (0.3)
248‡	ATLAS 7 TeV 4.6 fb^{-1}, W/Z combined cross sec.	[39]	34	287.3 (88.7)	8.4 (2.6)	13.7 (4.8)
249	CMS 8 TeV 18.8 fb^{-1} muon charge asymmetry A_{ch}	[83]	11	11.4 (12.1)	1.0 (1.1)	0.2 (0.4)
250	LHCb 8 TeV 2.0 fb^{-1} W/Z cross sec.	[84]	34	73.7 (59.4)	2.1 (1.7)	3.7 (2.6)
253	ATLAS 8 TeV 20.3 fb^{-1}, Z p_T cross sec.	[85]	27	30.2 (28.3)	1.1 (1.0)	0.5 (0.3)
542	CMS 7 TeV 5 fb^{-1}, single incl. jet cross sec., $R = 0.7$ (extended in y)	[86]	158	194.7 (188.6)	1.2 (1.2)	2.0 (1.7)
544	ATLAS 7 TeV 4.5 fb^{-1}, single incl. jet cross sec., $R = 0.6$	[9]	140	202.7 (203.0)	1.4 (1.5)	3.3 (3.4)
545	CMS 8 TeV 19.7 fb^{-1}, single incl. jet cross sec., $R = 0.7$, (extended in y)	[87]	185	210.3 (207.6)	1.1 (1.1)	1.3 (1.2)
573	CMS 8 TeV 19.7 fb^{-1}, $t\bar{t}$ norm. double-diff. top p_T and y cross sec.	[88]	16	18.9 (19.1)	1.2 (1.2)	0.6 (0.6)
580	ATLAS 8 TeV 20.3 fb^{-1}, $t\bar{t}$ p_T^t and $m_{t\bar{t}}$ abs. spectrum	[89]	15	9.4 (10.7)	0.6 (0.7)	−1.1 (−0.8)

Top-quark production measurements at the LHC 8TeV included in the CT18 global analysis.

Chosen such that:

- maximal amount of information included
- minimal conflict/tension with other data sets and among them

$t\bar{t}$ production kinematics in CT18



Jet and $t\bar{t}$ complement each other in the kinematic plane.
They impact the gluon PDF at large x. Important to disentangle the effect due to jet production and top-quark data.

Top and jet Data in CT18

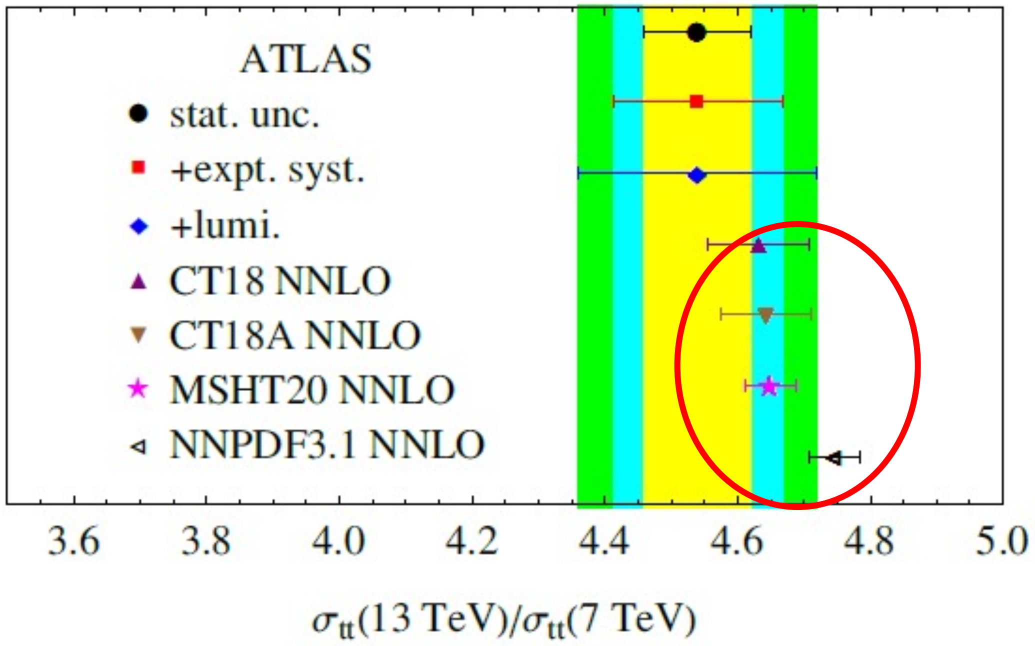
Top-quark
1511.04716 ATLAS 8 TeV tT pT diff. distributions
1511.04716 ATLAS 8 TeV tT mtT diff. distributions
1703.01630 CMS 8 TeV tT (pT , yt) 2d diff. distrib.

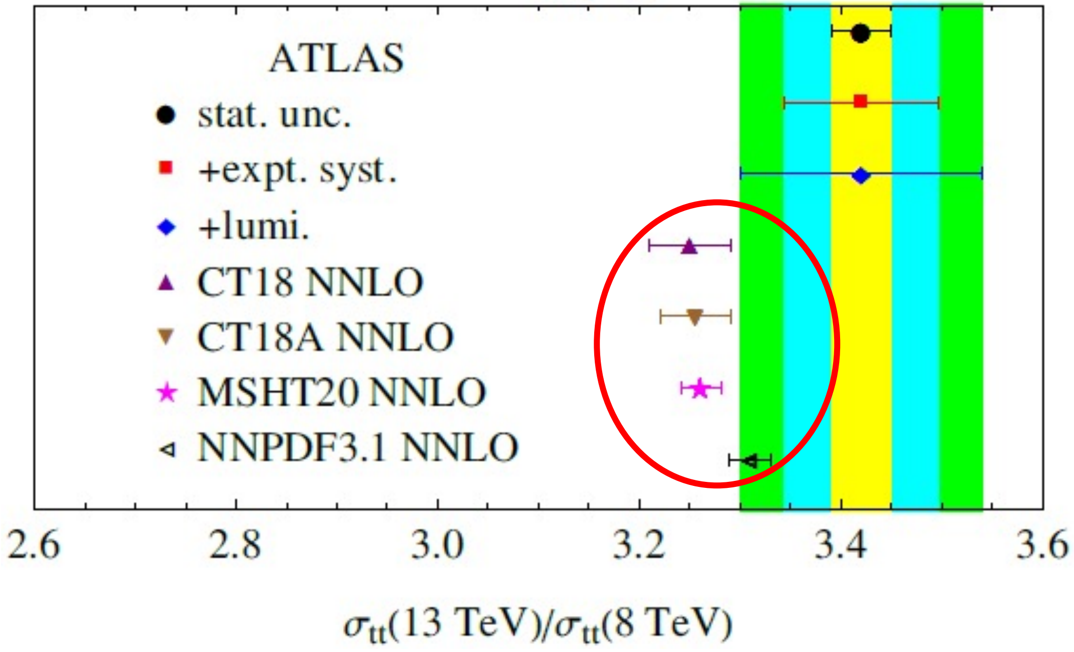
Jet production
1406.0324 CMS incl. jet at 7 TeV with R=0.7
1410.8857 ATLAS incl. jet at 7 TeV with R=0.6
1609.05331 CMS incl. jet at 8 TeV with R=0.7

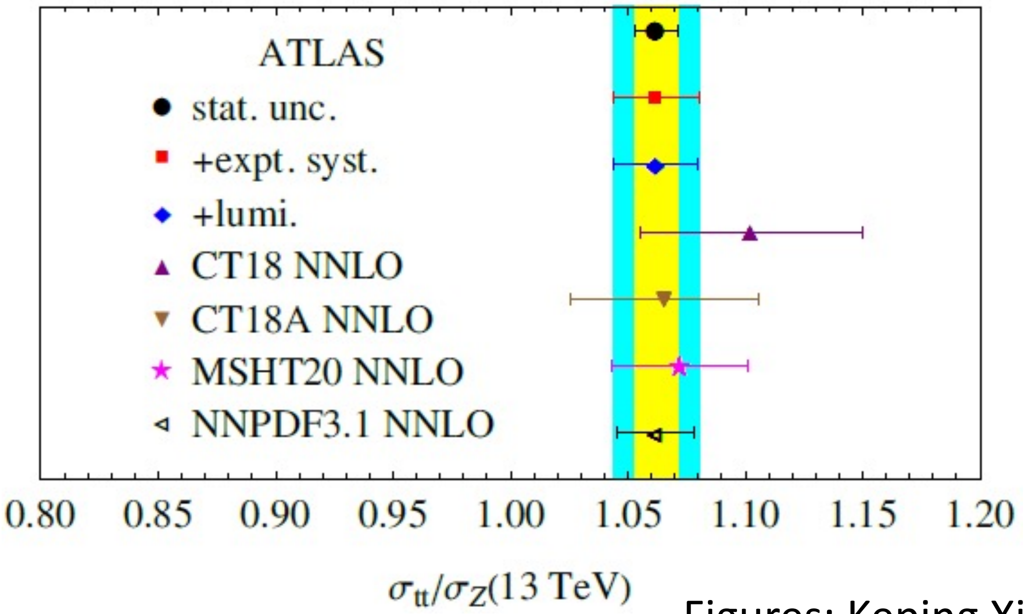
CT18 includes two $t\bar{t}$ 1D differential observables from ATLAS (using statistical correlations) and double differential measurements from CMS in order to include as much information as possible.
Some of the observables are in tension with each other.

What we learned from the CT18 global analysis

Ratios of NNLO $t\bar{t}$ and Z cross sections



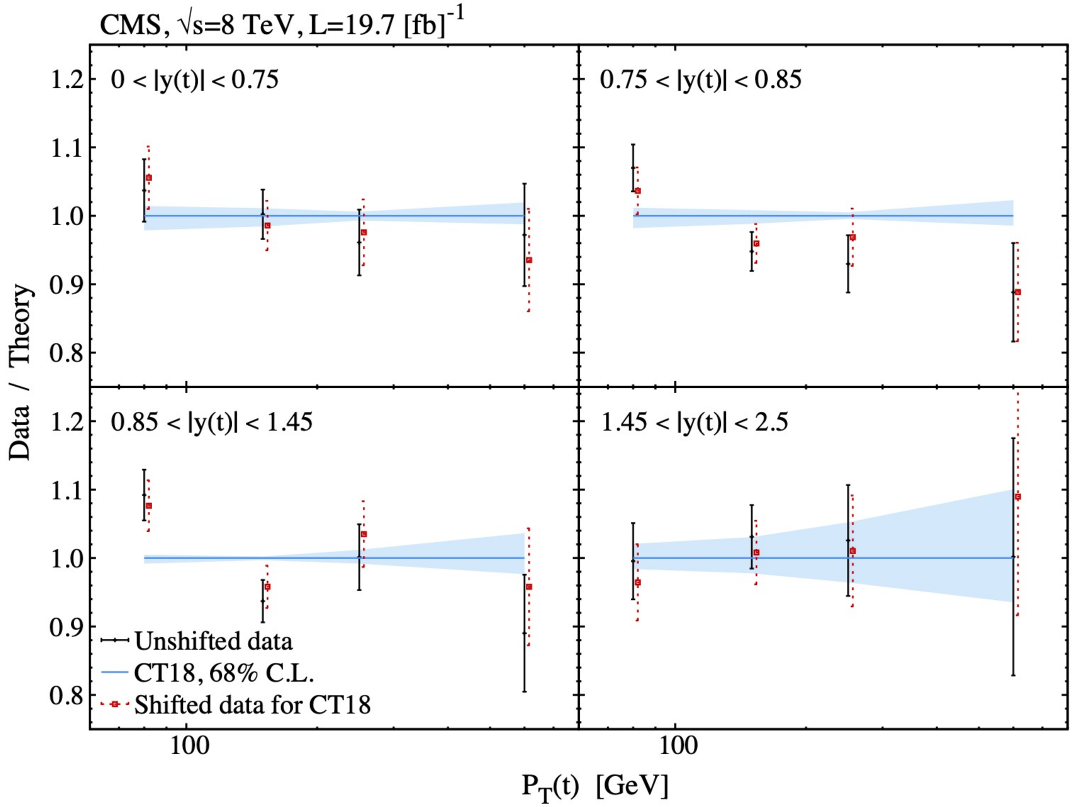




Some disagreement with $\sigma_{t\bar{t}}(8\ \mathrm{TeV})$?

Figures: Keping Xie

$t\bar{t}$ data at the LHC 8 TeV in CT18



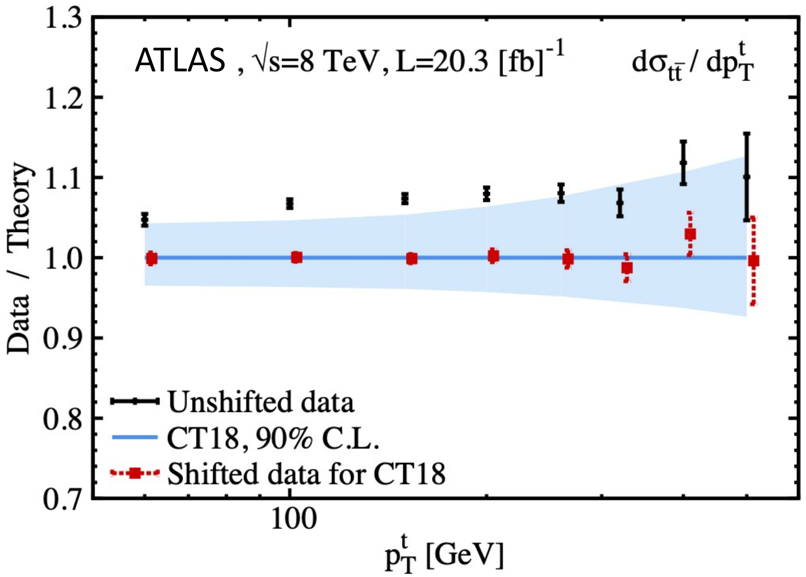
Effect of correlated errors in fitting the CMS data is relatively minimal.

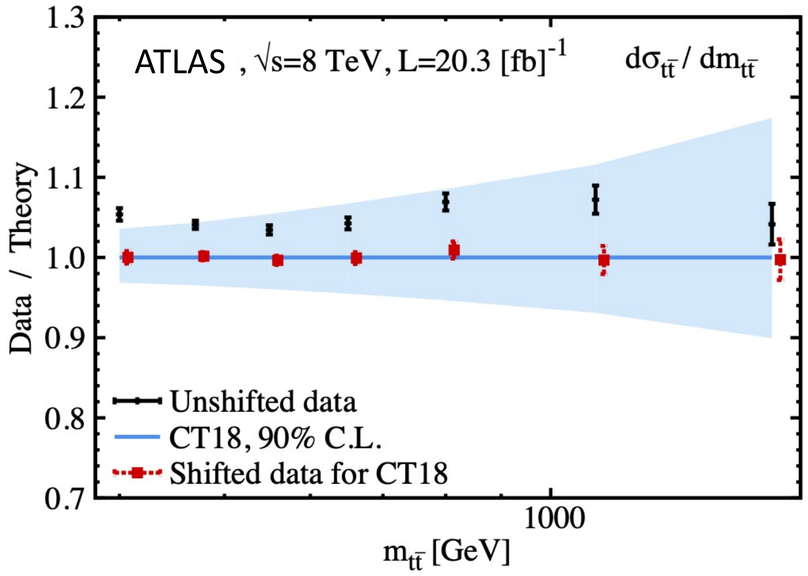
Good description of the analogous ATLAS pTt and mtt critically depends on the use of nuisance parameters to compensate for correlated systematics.

Observed effect on the CT18 PDFs is modest, when ttbar data are included together with the Tevatron and LHC jet production.

Inclusion of 1d or 2d differential Xsec would not lead to a significant reduction of the CT18 PDF uncertainty.

Impact on the gluon PDF compatible with the jet data. Jet data provide stronger constraints due to their larger numbers of data points, wider kinematic range, and relatively small statistical and systematic errors.



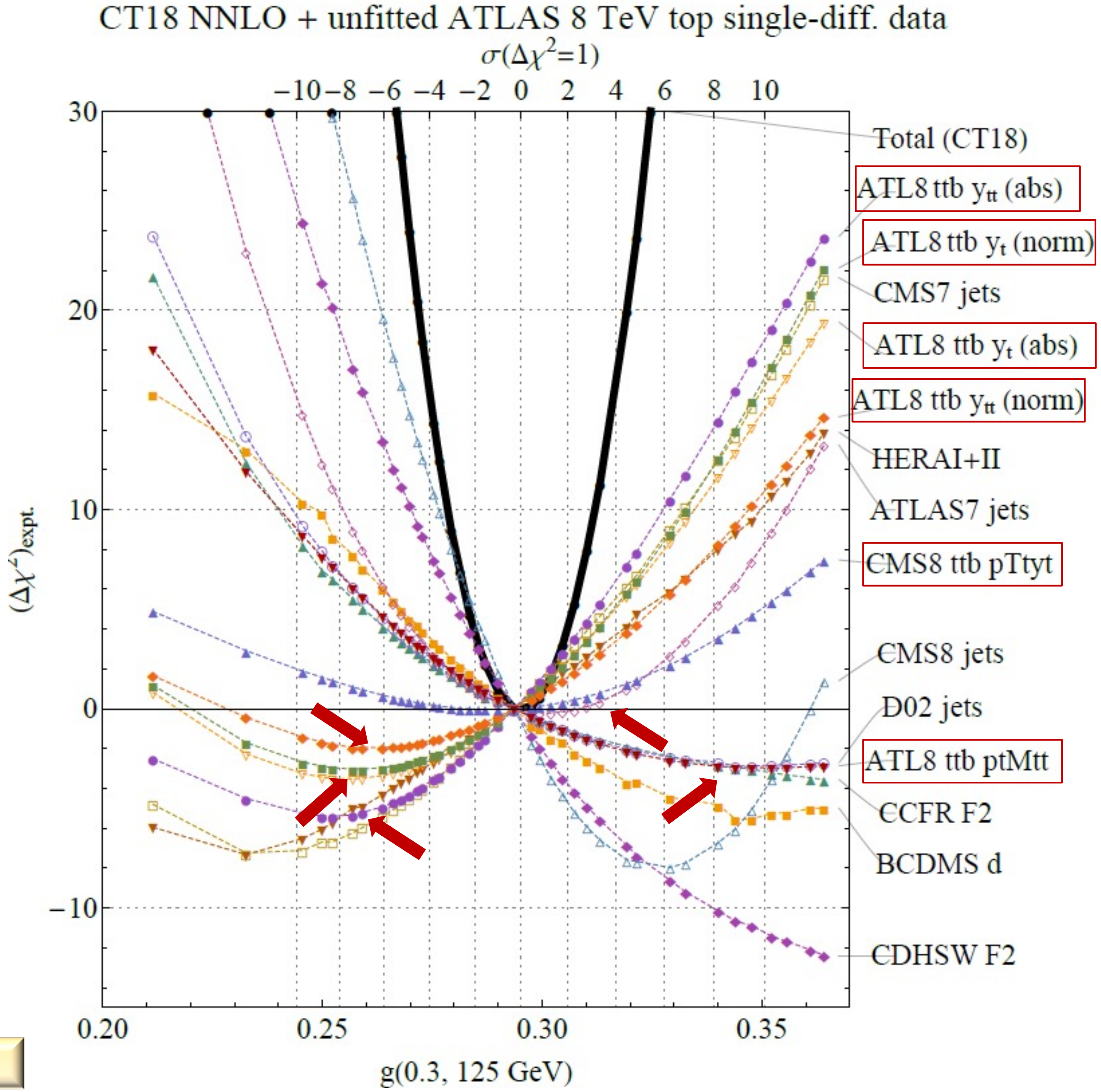


CT18, PRD 2021

Lagrange Multiplier scan: $g(x = 0.3, 125\ \text{GeV})$

In under-constrained directions, the Lagrange Multiplier method complements the Hessian approach.

There is some tension between the ttbar observables that leads to different pulls on the gluon distribution that each prefers.



Fair overall agreement. But observe strong opposite pulls from CMS7 and CMS8+ATLAS7 jet production data sets

$t\bar{t}$ production: ATLAS8 $y_{t\bar{t}}$ and y_t distributions (absolute or normalized) agree with HERA DIS, oppose ATLAS8 $\mathrm{d}^2\sigma/(dp_{T,t}dm_{t\bar{t}})$ and CMS8 $\mathrm{d}^2\sigma/(dp_{T,t}dy_{t,ave})$

6500 core hours

Figure: P. Nadolsky

LHC 13 TeV $t\bar{t}$ measurements in CT18NNLO

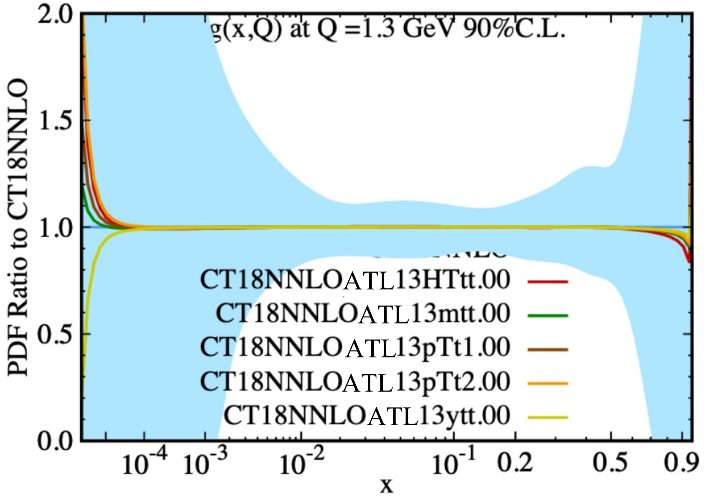
- JHEP 1902 (2019) 149, 2019 - arXiv:1811.06625
  CMS: Measurements of $t\bar{t}$ differential cross sections at 13 TeV using events containing two leptons (1D); 35.9 fb^{-1}IL
- JHEP 01 (2021) 033, 2021 - arXiv: 2006.09274
  ATL: Measurements of $t\bar{t}$ differential cross-sections at 13 TeV in the all-hadronic channel (1D); 36.1 fb^{-1} IL

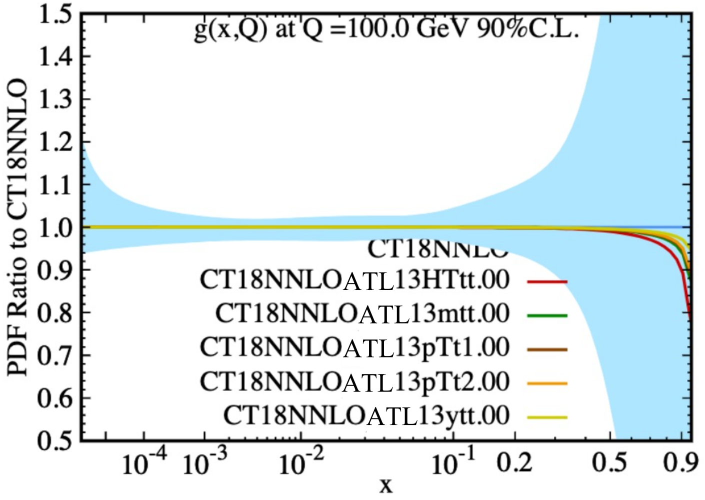
Label in data list	Npt	N. Corr sys unc	Exp	Corr Sys
5 20 ATL13mtt	9	67	ATLAS	Nuisance par: given
5 21 ATL13ytt	12	67	ATLAS	Nuisance par: given
5 22 ATL13HTtt	11	67	ATLAS	Nuisance par: given
5 23 ATL13pTt1	10	67	ATLAS	Nuisance par: given
5 24 ATL13pTt2	8	67	ATLAS	Nuisance par: given
5 25 CMS13mtt	7	6	CMS	Nuisan par: Sigma-K dec
5 26 CMS13pTt	6	5	CMS	Nuisan par: Sigma-K dec
5 27 CMS13yt	10	9	CMS	Nuisan par: Sigma-K dec
5 28 CMS13ytt	10	9	CMS	Nuisan par: Sigma-K dec

These are full phase space absolute measurements

ePump gluon PDF from ATLAS and CMS 13 TeV $t\bar{t}$ data

ATLAS 13 TeV



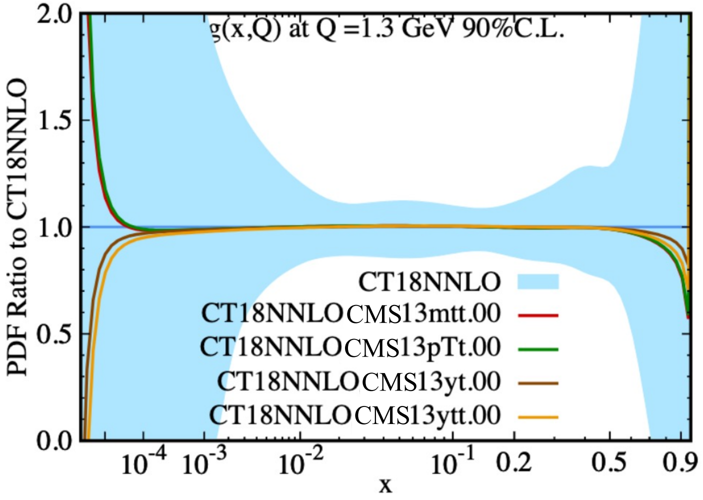


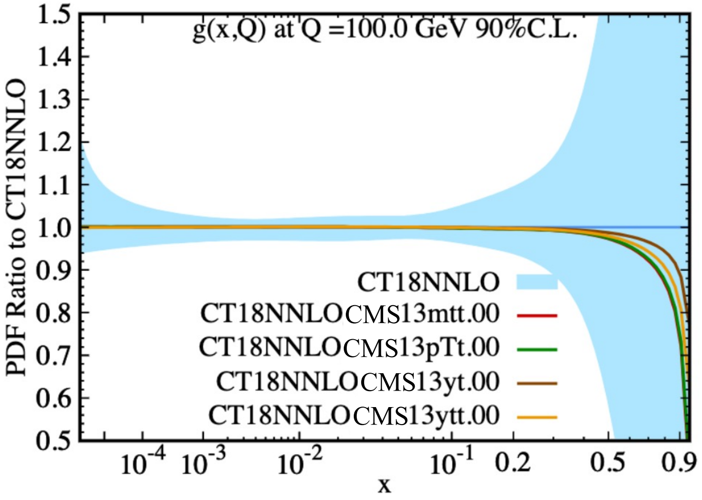
Here, data are included individually one at a time.

Error PDF Updating Method (ePump):
impact from each individual data set from
ATL and CMS at large x, (x > 0.5) at Q=100 GeV.

Pulls from different distributions at large x
seem to be consistent in ePump

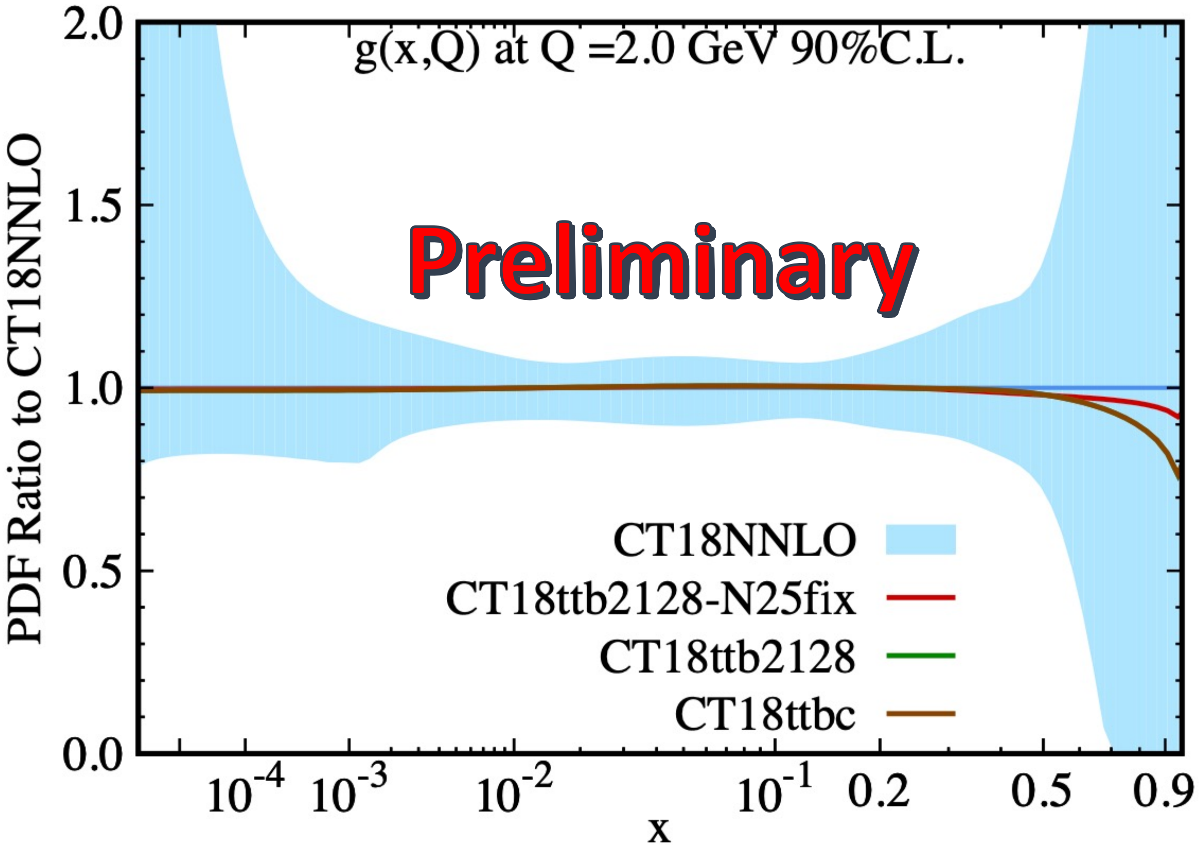
CMS 13 TeV

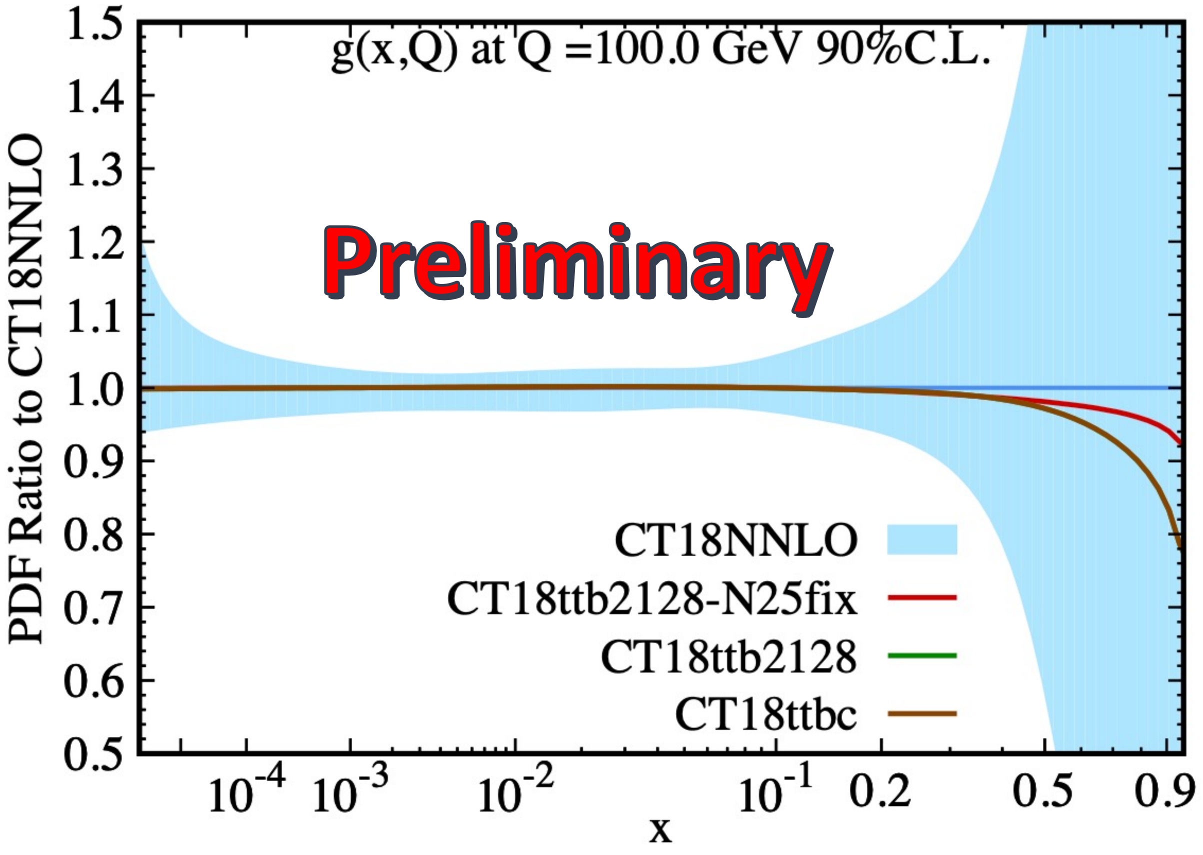




CT18NNLO 90% C.L.

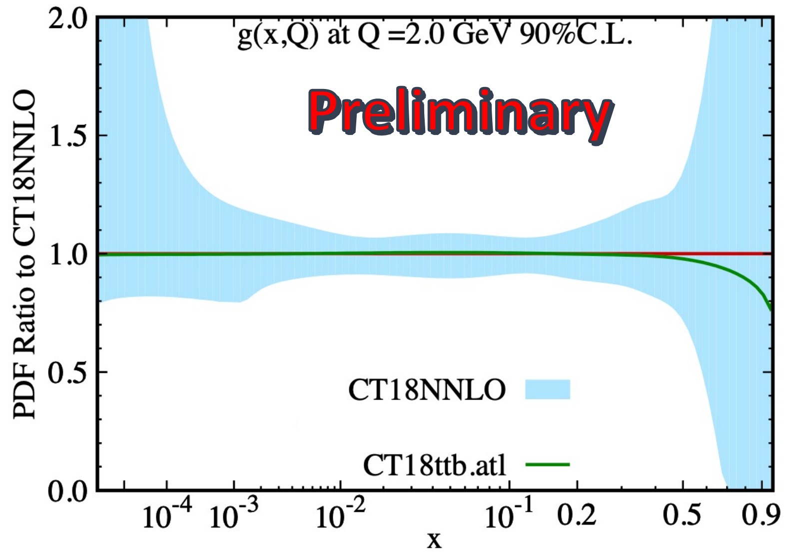
Global fit: Impact from ytt 1D from CMS + ATLAS

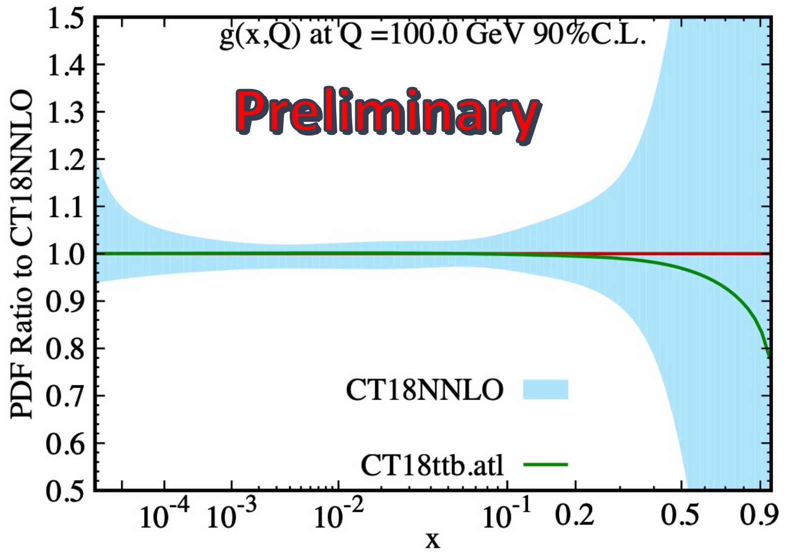





```
./CT18ttbc.dta: DATA SET 521 ; NORM Fac =   1.00000 ; # of pts =   12 ; chi^2 =    12.796140 S=    0.29377 chi^2/N =    1.06634
./CT18ttbc.dta: DATA SET 528 ; NORM Fac =   1.00000 ; # of pts =   10 ; chi^2 =     6.415790 S=   -0.77071 chi^2/N =    0.64158
```

Global fit: Impact from all ATL 1D: ytt, mtt pT1, pT2, Htt

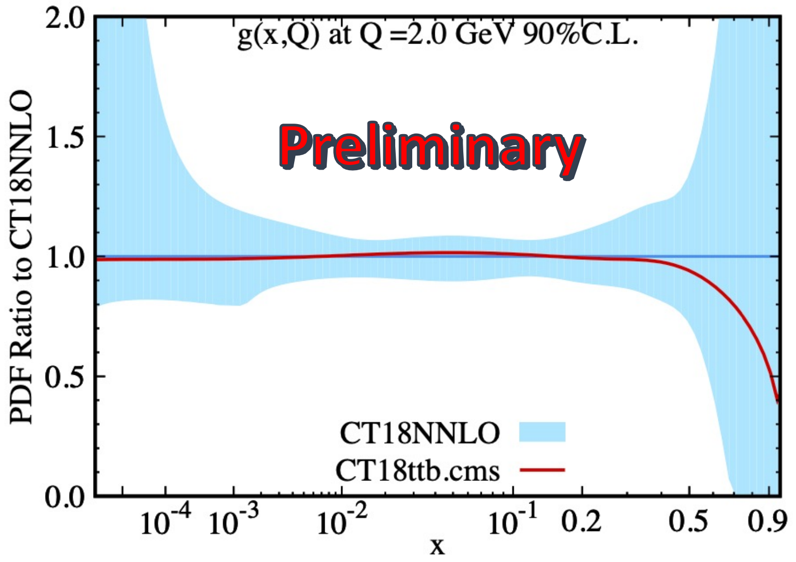


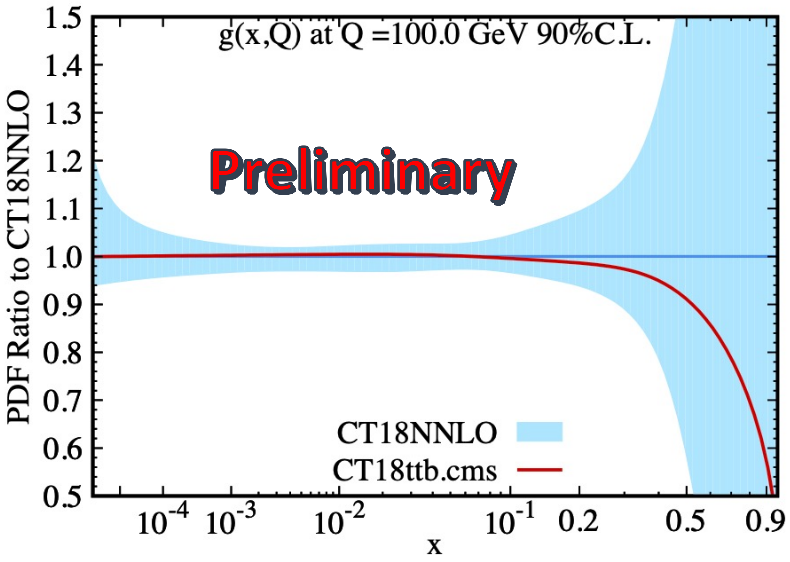



```
ATLAS
 mtt  DATA SET 520 ; chi^2/N = 1.45793
 ytt  DATA SET 521 ; chi^2/N = 1.06780
 HTtt DATA SET 522 ; chi^2/N = 1.72802
 pTt1 DATA SET 523 ; chi^2/N = 1.32391
 pTt2 DATA SET 524 ; chi^2/N = 1.58153
```

For now, data sets from each Experiment are included with no statistical correlations

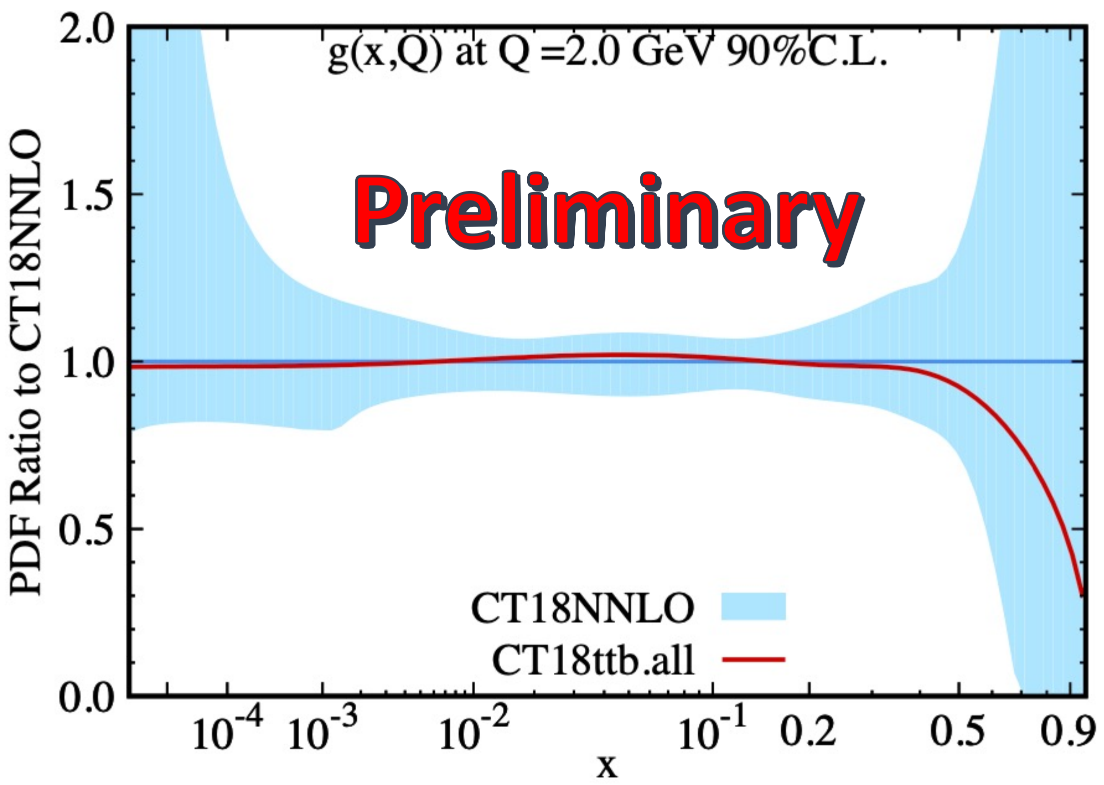
Global fit Impact from all CMS 1D: yt, mtt pTt, ytt

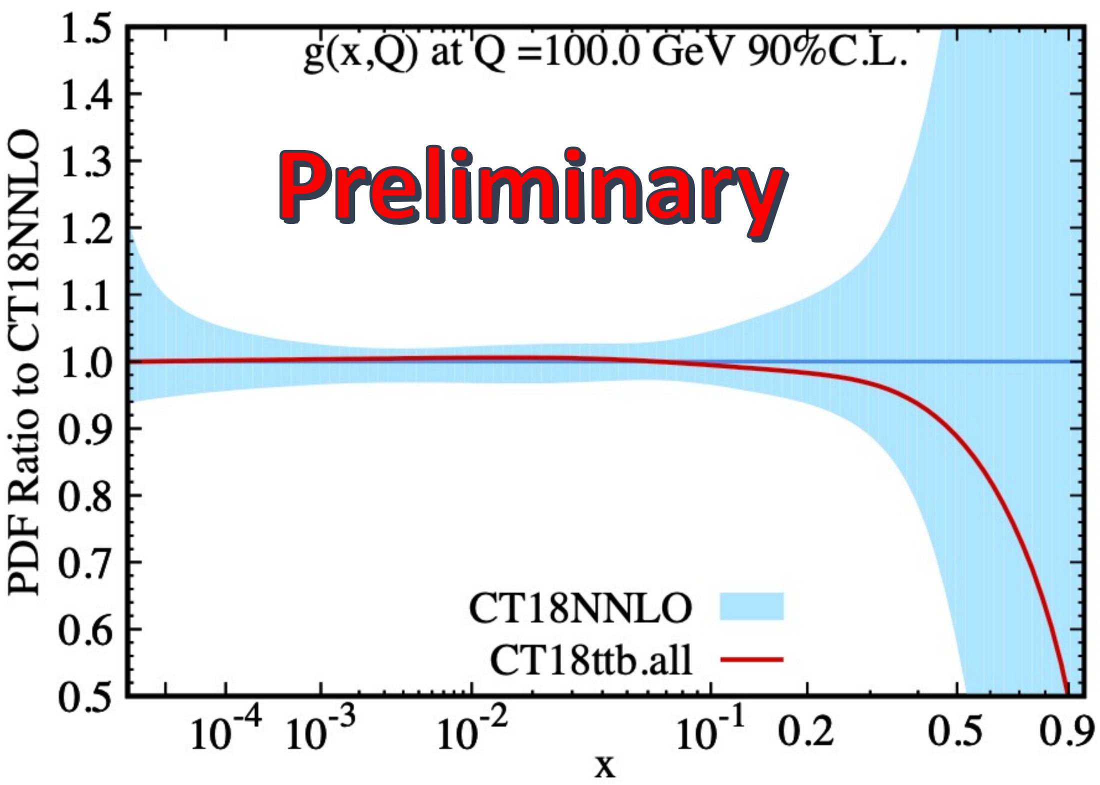





```
CMS
mtt DATA SET 525 ; chi^2/N = 3.02887
pTt DATA SET 526 ; chi^2/N = 2.90375
yt  DATA SET 527 ; chi^2/N = 0.63991
ytt DATA SET 528 ; chi^2/N = 0.55449
```

Global fit: Impact from all $t\bar{t}$ data at 13 TeV ATL+CMS





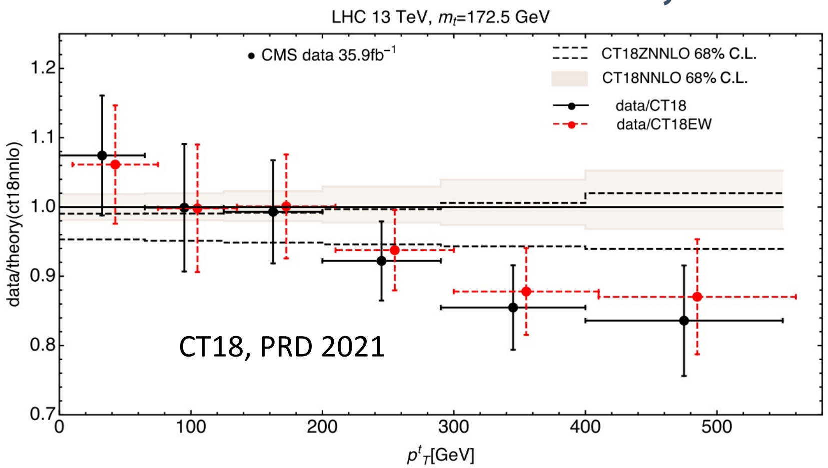

```
ATL mtt  DATA SET 520 ;  chi^2/N = 1.42643
ATL ytt  DATA SET 521 ;  chi^2/N = 1.05387
ATL HTtt DATA SET 522 ;  chi^2/N = 1.67374
ATL pTt1 DATA SET 523 ;  chi^2/N = 1.29656
ATL pTt2 DATA SET 524 ;  chi^2/N = 1.55261
CMS mtt  DATA SET 525 ;  chi^2/N = 2.96862
CMS pTt  DATA SET 526 ;  chi^2/N = 2.83397
CMS yt   DATA SET 527 ;  chi^2/N = 0.62119
CMS ytt  DATA SET 528 ;  chi^2/N = 0.52401
```

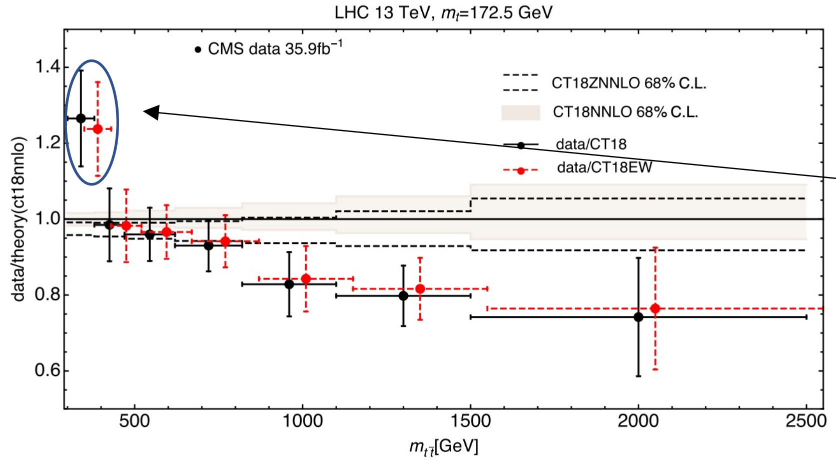
Cumulative impact: gluon affected at $x > 0.1$
Small impact at intermediate x

$t\bar{t}$ @ LHC 13 TeV: Data vs Theory

Distributions consistent with softer gluon at large x

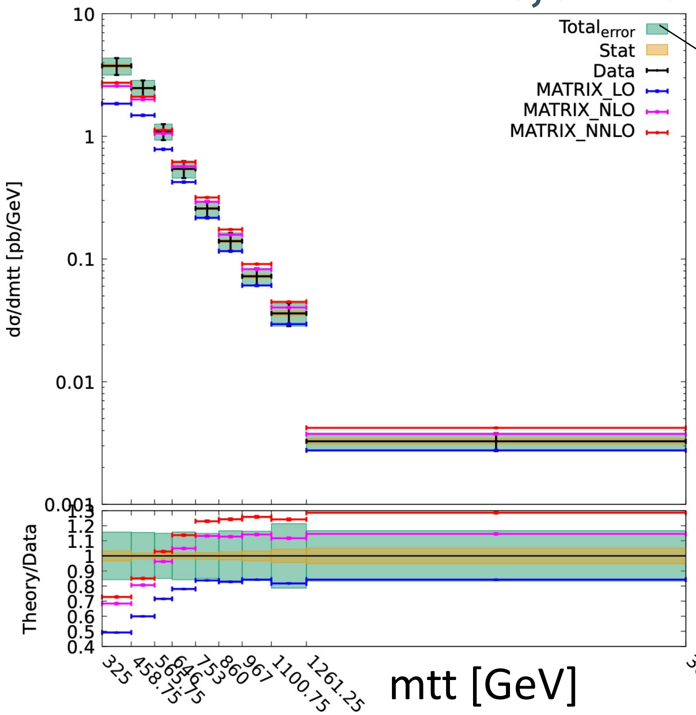
CMS, JHEP 02 (2019) 149, 2019





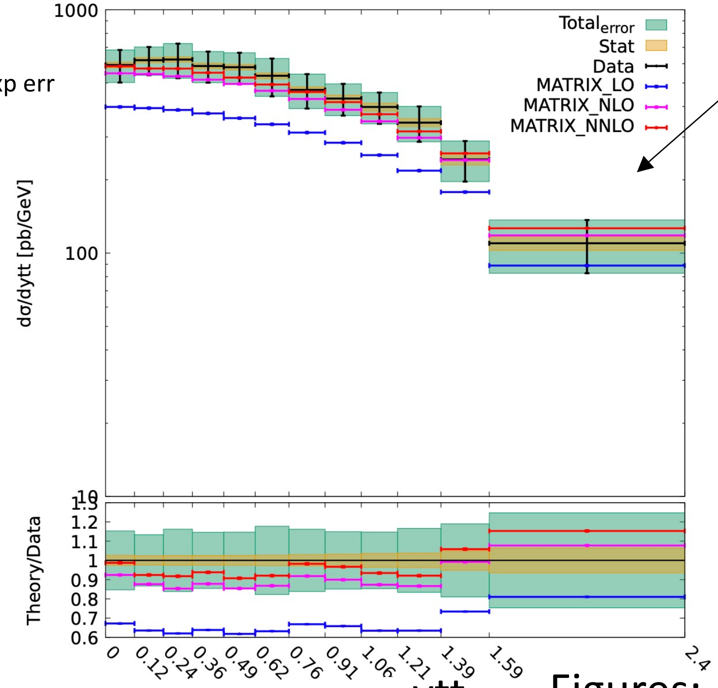
Sensitive to the reconstruction of the top quark from particle-level final states (Czakon, Mitov, Poncelet, 2008.11133)

ATLAS, JHEP 01 (2021) 033, 2021



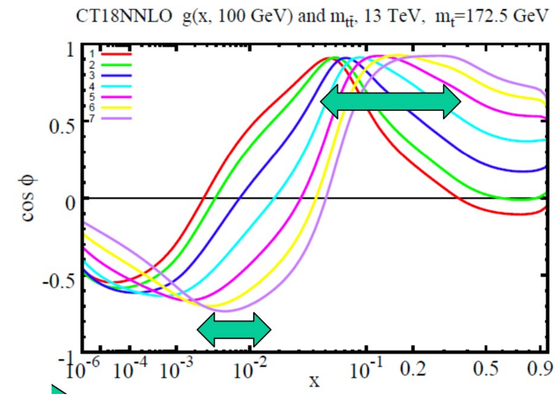
Tot exp err

mtt [GeV]



ytt

Theory predictions obtained with MATRIX (S. Catani, S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli, H. Sargsyan, 1901.04005, 1906.06535)



$d\sigma/dm_{t\bar{t}}$

- Sensitive to g-PDF at x in [0.05-0.5] and around 0.01

ePump correlation plot for the mtt distrib.

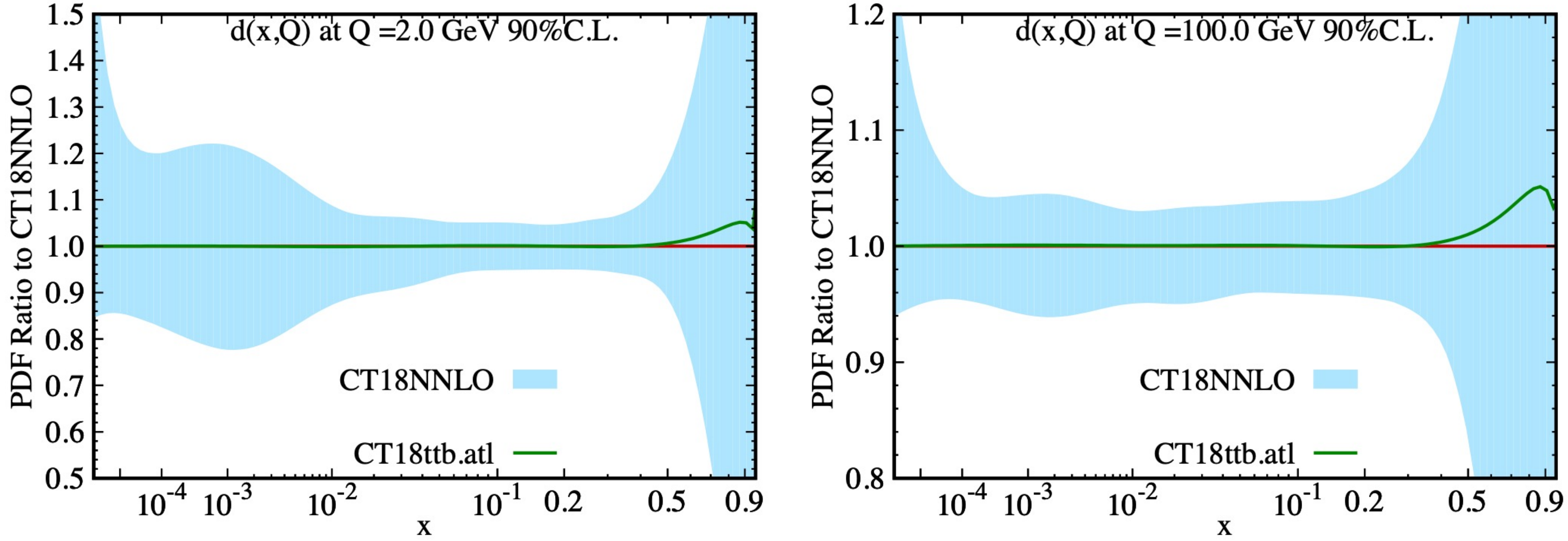
Figures: Alim Ablat

Discussion: Conclusions and the Big Picture

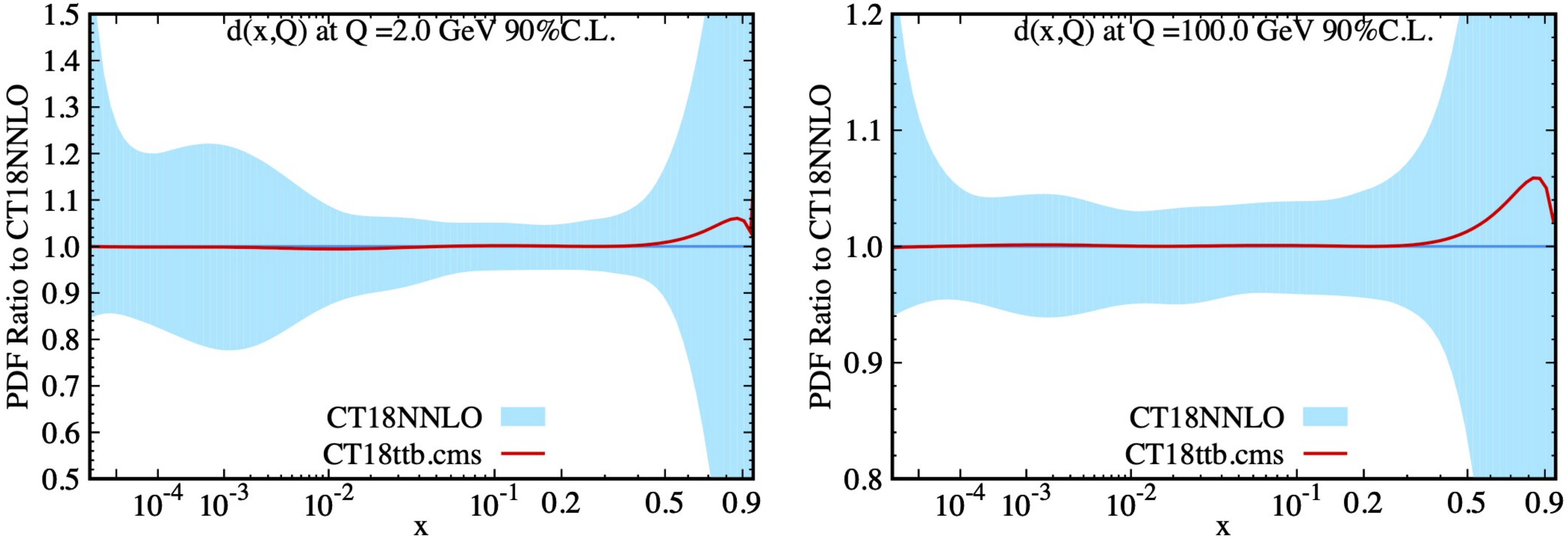
- We discussed the impact of top-quark pair production at LHC data on CTEQ-PDFs
- $t\bar{t}$ measurements are critical to understand the gluon at large x
- Precise new data available from ATLAS and CMS at LHC run II need to be fully exploited together with information about systematic errors
- Impact of $t\bar{t}$ production at the LHC 13 TeV will further complement that of jet data on the gluon PDF.
- $t\bar{t}$ and jets overlap in the Q-x plane, but matrix elements and phase space suppression are different and constraints on the gluon PDF may be placed at different values of x.
- Detailed information on both covariance and nuisance parameter representations for experimental errors is critical for full exploitation of data in PDF determinations
- Critical to Constrain m_t, α_s, g correlations

BACKUP

Impact from all ATL 1D: ytt, mtt pT1, pT2, Htt



Impact from all CMS 1D: yt, mtt pTt, ytt



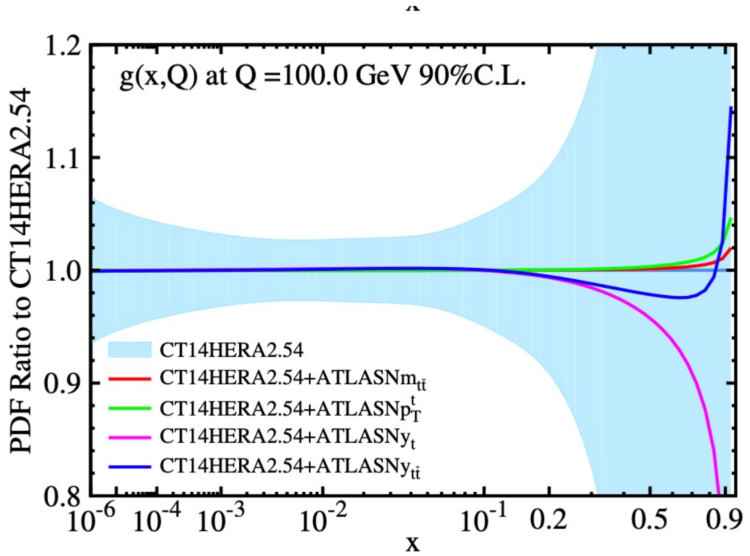
There is a compensating effect on other PDFs, e.g., *d* and *dv*

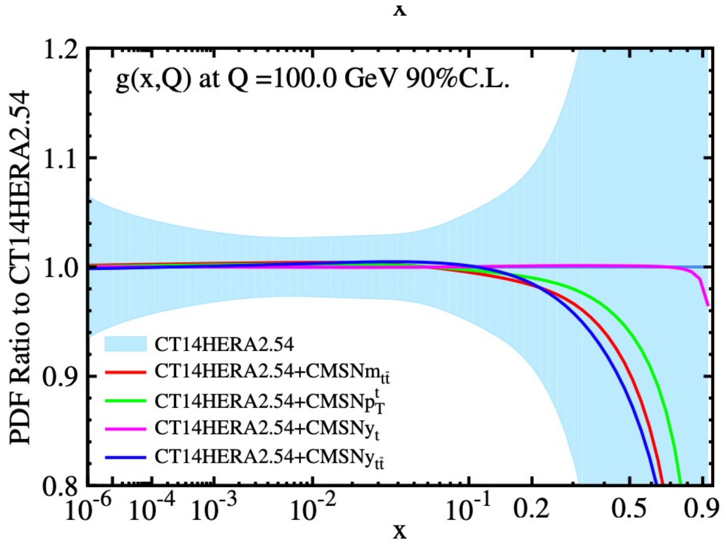
Recent CTEQ related exploratory studies with ePump

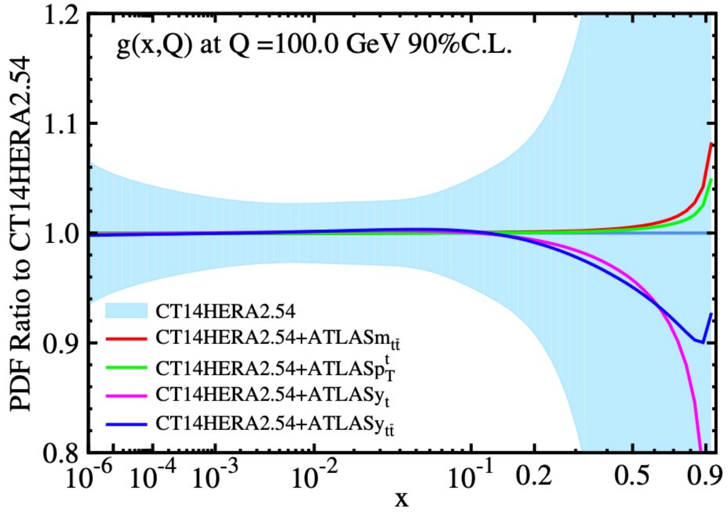
- 1912.08801 (Czakon, Dulat, Hou, et. al.) Exploratory study of 8 TeV $t\bar{t}$ 2D diff. Distrib. @CMS with ePump (Error PDF Updating Method) code.
- 2003.13740 (Kadir, Ablat, Dulat, Hou, Sitiwaldi) Impact of 8 TeV $t\bar{t}$ 1D diff distrib. @ATLAS and CMS with ePump

- Differential distributions provide minor constraints on the gluon PDF when inclusive jet production data are included in the analysis. The impact depends on what data baseline is used.

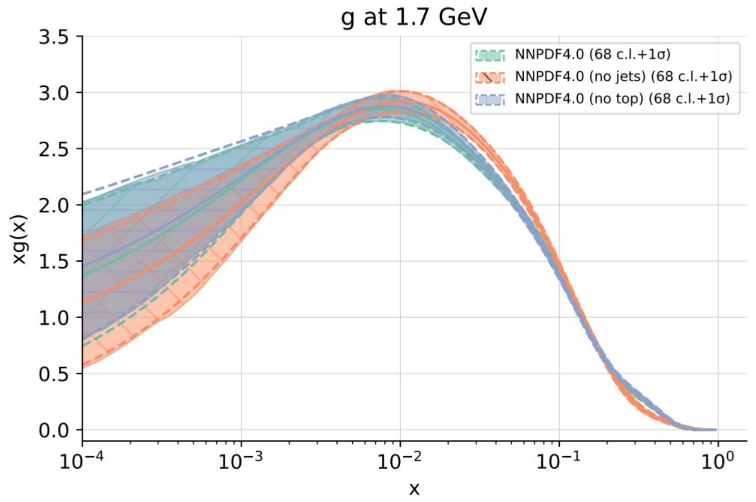
- Pulls in different directions at large x observed for different distributions





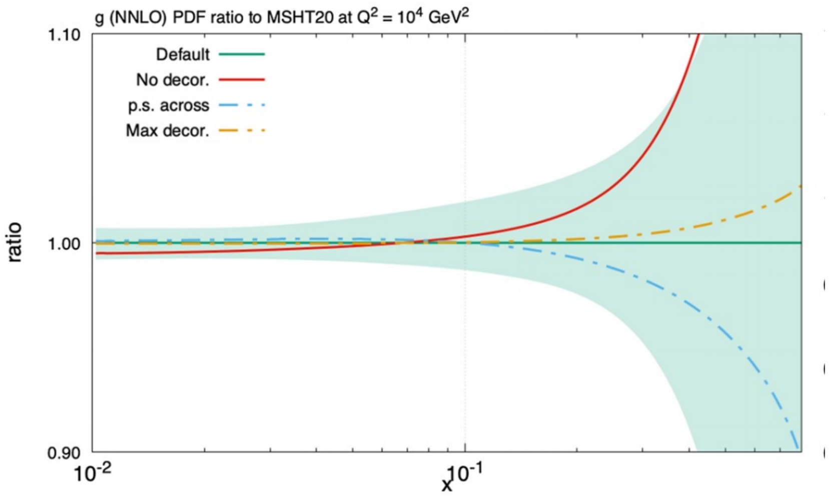


Results from other PDF groups



NNPDF Coll. Forthcoming NNPDF4.0 (Figure: E. Nocera's talk at DIS2021)

$t\bar{t}$: while there is overall agreement between CT18 and other groups, NNPDF and MSHT have observed more impact from $t\bar{t}$ observables in their fits.

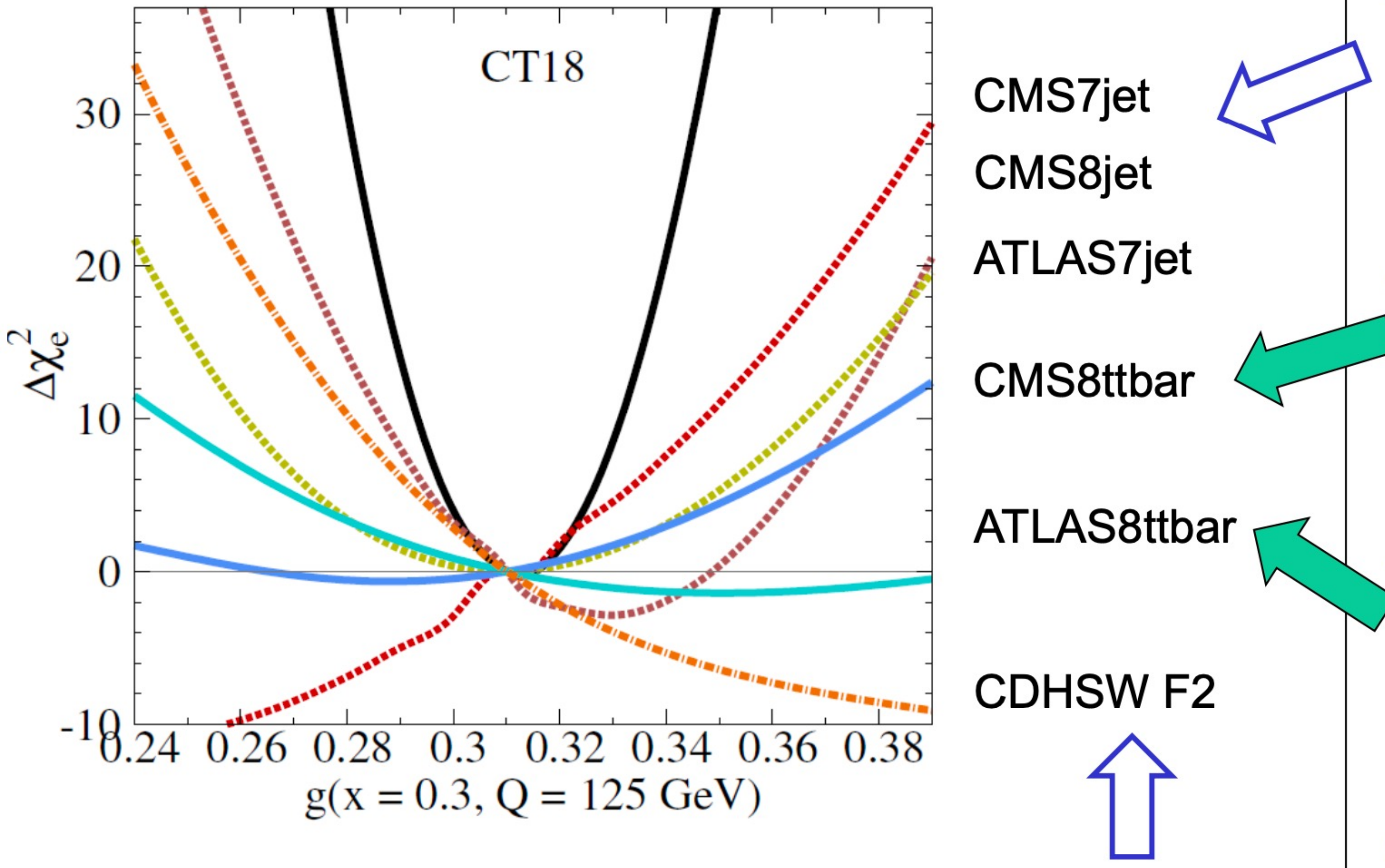


MSHT20 (Figure: Bailey, Cridge et. al. EPJC 2021, 2012.04684)

Difficulties in fitting simultaneously the ATLAS 8 TeV pTt, yt, mtt, ytt distributions due to systematic PS errors. The parton-shower error has been decorrelated across bins to improve the description.

In more details

g(x=0.3; Q=125 GeV)



Lagrange Multiplier Scans

- At large x=0.3, Q=125 GeV, CMS + ATLAS jet data and CDHSW F2 data dominate the constraint on g-PDF.
- CMS 8 TeV t-tbar (pT_t,y_t) data provides similar constraint as HERA I+II data on g-PDF, favoring softer gluon.
- ATLAS 8 TeV t-tbar (pT_t ,M_tt) data provides similar constraint as D0 Run 2 jet data on g-PDF, favoring harder gluon.
- Some tension found in CMS7 (favoring softer gluon) and CMS8 (favoring harder gluon) jet data.